National Aeronautics and
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GeoSTAR Progress Report

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Summary

- **GeoSTAR is a microwave sounder intended for GEO**
  - Ground-based prototype under development
  - Space-based version will be developed in time for GOES-S (2014)
  - Configuration suitable for MEO ("MeoSTAR") is also under study
- **Functionally equivalent to AMSU**
  - Tropospheric T-sounding @ 50 GHz with ≤ 50 km resolution
    - *Stand-alone all-weather temperature soundings*
    - Cloud clearing of IR sounder
  - Tropospheric q-sounding @ 183 GHz with ≤ 25 km resolution
    - *Stand-alone all-weather water vapor/liquid water soundings*
    - *Rain mapping*
    - *Tropospheric wind profiles* (Only feasible from GEO)
- **Using *Aperture Synthesis***
  - Also called Synthetic Thinned Array Radiometer (STAR)
  - Also called Synthetic Aperture Microwave Sounder (SAMS)

Why?

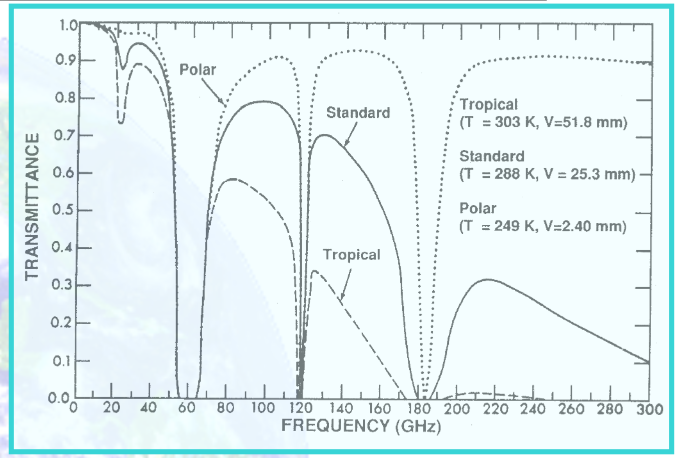
- **GEO sounders complement LEO sounders**
  - LEO: Global coverage, but poor temporal resolution; high spatial res. is easy
  - GEO: High temporal resolution and coverage, but only hemispheric non-polar coverage; high spatial res. is difficult
  - Requires equivalent measurement capabilities as now in LEO: IR + MW
- **Enable full sounding capability from GEO**
  - Complement primary IR sounder (HES/GIFTS) with matching MW sounder
    - Until now not feasible due to very large aperture required (~ 4-5 m dia. in GEO)
  - Microwave provides cloud clearing information
    - Requires T-sounding through clouds - to surface under all atmospheric conditions
- **MW sounders measure quantities IR sounders can't**
  - Precipitation
  - Cloud liquid water
  - Meteorologically "interesting" scenes
    - Full cloud cover
    - Storms & hurricanes

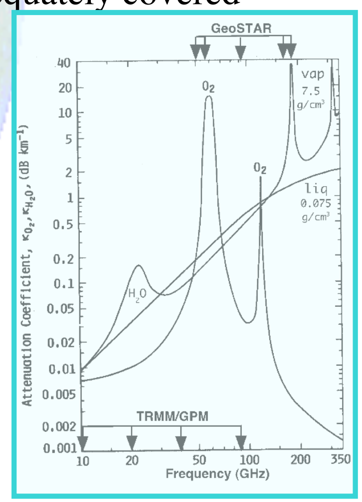
Why No MW/GEO Sounder Already?

- **Difficult to build large enough aperture**
  - AMSU-equivalence requires 6 meter parabolic dish
    - Difficult to stow and deploy
  - High surface fidelity required for adequate beam efficiency
    - Beam efficiency of 95%+ required for sounding
  - Mesh or film technology not available at sounding frequencies
    - Must use solid dish
    - Means large volume and mass
- **Difficult to achieve adequate spatial coverage**
  - Dish antenna must be mechanically scanned
    - Difficult to scan very large dish
  - Scanning subreflector is problematic
    - Beam quality/efficiency degrades with scan angle
    - Therefore, scan range is limited
- **Difficult to overcome system limitations**
  - Mechanical scanning causes platform disturbances
    - Cannot coexist with super-high resolution imagers
  - Large platform resources required
    - Mass, power, volume, platform control
  - High risk at system level
  - Difficult to expand to meet future growing needs

Measurement Requirements

- **Radiometric sensitivity**
  - Must be no worse than AMSU (≤ 1 K)
- **Spatial resolution**
  - At nadir: ≤ 50 km for T; ≤ 25 km for q
- **Spectral coverage**
  - Tropospheric T-sounding: Must use 50-56 GHz
    - Note: Higher frequencies (118 GHz, etc.) cannot penetrate to the surface everywhere (e.g., tropics)
    - Bottom 2 km (PBL) is the most important/difficult part and must be adequately covered
  - Tropospheric q-sounding: Must use 183 GHz (AMSU-B channels)
    - Note: Higher frequencies (325 or 450 GHz) cannot penetrate even moderate atmospheres
  - Convective rain: 183 GHz (AMSU-B channels) method proven
  - "Warm rain": 89 + 150 GHz (Grody) - *maybe 50+150*
- **Temporal coverage from GEO**
  - T-sounding: Every hour @ 50 km resolution *or better*
  - Q-sounding: Every 30 minutes @ 25 km resolution *or better*





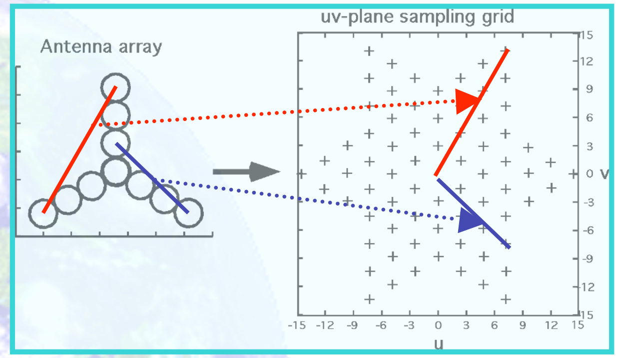
Functionality & Benefits of GeoSTAR

These are the performance goals for GeoSTAR #1 (to be improved by x2 next):

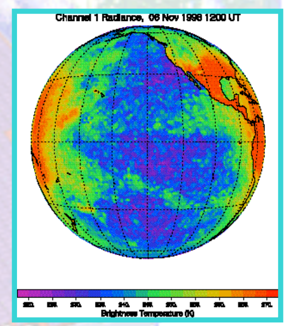
- **All-weather soundings @ 2 km vertical resolution**
  - Full hemisphere @ ≤ 50/30 km every 30-60 min (continuous) - *easily improved*
  - Standalone soundings; also complements any GEO IR sounder
- **Rain**
  - Full hemisphere @ ≤ 30 km every 30 min (continuous) - easily improved
  - Measurements: scattering/absorption from raindrops (stratiform) or ice (convective)
  - Real time tracking: full hemispheric view every 5 minutes
- **Tropospheric wind profiling**
  - Surface to 300 mb; adjustable pressure levels; in & below clouds
  - Primarily horizontal winds vectors (at pressure levels)
  - *Very high temporal resolution possible*
  - Vertical winds may also be feasible - requires some research
- **Rapid-cycle NRT storm tracking**
  - Scattering signal from hurricanes/convection detectable in < 5 minutes
    - Use to estimate location & intensity of convective centers
  - Switch to detect/track mode -> Update every 5 minutes (continuous)

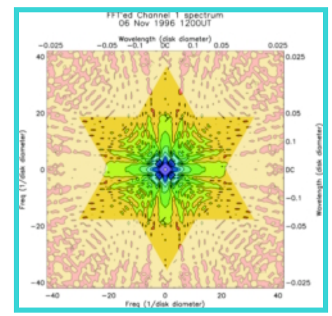
GeoSTAR System Concept

- **Concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3λ wide (2 cm @ 50 GHz)
  - Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
  - One "Y" per band, interleaved
- **Other subsystems**
  - A/D converter; Radiometric power measurements
  - Cross-correlator - massively parallel multipliers
  - On-board phase calibration
  - Controller: accumulator -> low D/L bandwidth



Receiver array & Resulting uv samples





Example: AMSU-A ch. 1

Aperture Synthesis Is Not New

Very Large Array (VLA) at National Radio Astronomy Observatory (NRAO)

In operation for many years

Others Are Developing STAR for Space

ESA's Soil Moisture and Ocean Salinity (SMOS)

L-band system under development - Launch in 2007

What GeoSTAR Measures

- **Visibility measurements**
  - Essentially the same as the spatial Fourier transform of the radiometric field
  - Measured at fixed uv-plane sampling points - One point for each pair of receivers
  - Both components (Re, Im) of complex visibilities measured
  - Visibility = Cross-correlation = Digital 1-bit multiplications @ 100 MHz
  - Visibilities are accumulated over calibration cycles —> Low data rate
- **Calibration measurements**
  - Multiple sources and combinations
  - Measured every 20-30 seconds = calibration cycle
- **Interferometric imaging**
  - All visibilities are measured simultaneously - On-board massively parallel process
  - Accumulated on ground over several minutes, to achieve desired NEDT
  - 2-D Fourier transform of 2-D radiometric image is formed - *without scanning*
- **Spectral coverage**
  - Spectral channels are measured one at a time - LO tunes system to each channel

Calibration

- **GeoSTAR is an *interferometric* system**
  - Therefore, *phase calibration* is most important
  - System is designed to maintain phase stability for tens of seconds to minutes
  - Phase properties are monitored beyond stability period (e.g., every 20 seconds)
- **Multiple calibration methods**
  - Common noise signal distributed to multiple receivers —> complete correlation
  - Random noise source in each receiver —> complete de-correlation
  - Environmental noise sources monitored (e.g., sun's transit, Earth's limb)
  - Occasional ground-beacon noise signal transmitted from fixed location
  - Other methods, as used in radio astronomy
- **Absolute radiometric calibration**
  - One conventional Dicke switched receiver measures "zero baseline visibility"
    - Same as Earth disk mean brightness temperature (= Fourier offset)
  - Also: compare with equivalent AMSU observations during over/under-pass
  - The Earth mean brightness is highly stable, changing extremely slowly

GeoSTAR Data Processing

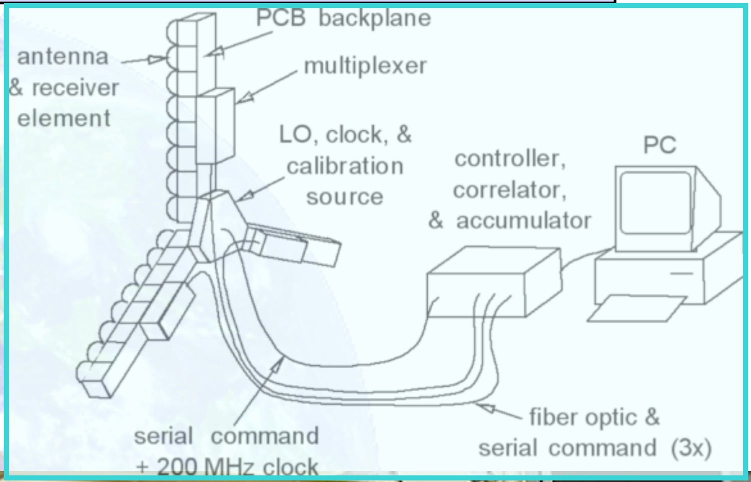
- **On-board measurements**
  - Instantaneous visibilities: high-speed cross-correlations
  - Accumulated visibilities: accumulated over calibration cycles
  - Calibration measurements
- **On-ground image reconstruction**
  - Apply phase calibration: Align calibration-cycle visibility subtotals
  - Accumulate aligned visibilities over longer period —> Calibrated visibility image
- **On-ground image reconstruction**
  - Inverse Fourier transform of visibility image, for each channel
  - Complexities due to non-perfect transfer functions are taken into account
- **On-ground geophysical retrievals**
  - Conventional approach
  - Applied at each radiometric-image grid point

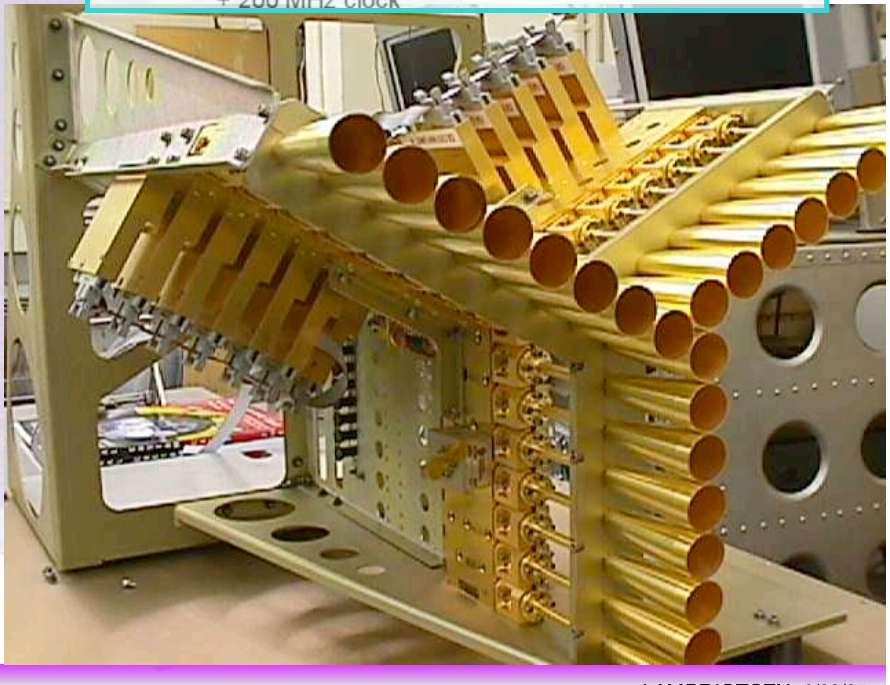
Technology Development

- **MMIC receivers**
  - Required: Small (2 cm wide ‘slices’ @ 50 GHz), low power, low cost
  - Status: Receivers off-the-shelf @ < 100 GHz; Chips available up to 200 GHz
- **Correlator chips**
  - Required: Fast, low power, high density
  - Status: Real chips developed for IIP & GPM; Now 0.5 mW per 1-bit @ 100 MHz
- **Calibration**
  - Required: On-board, on-ground, post-process
  - Status: Will implement & demo GEO/SAMS design in Proto-GeoSTAR
- **System**
  - Required: Accurate image reconstruction (Brightness temps from correlations)
  - Status: Will demonstrate capability with Proto-GeoSTAR
- **Related efforts: Rapidly maturing approach & technology**
  - European L-band SMOS now in Phase B; to be launched ~2007
  - NASA X/K-band aircraft demo (LRR): candidate for GPM constellation
  - NASA technology development efforts (IIP, etc.); various stages of completion

GeoSTAR Prototype Development

- **Objectives**
  - Technology risk reduction
  - Develop system to maturity and test performance
  - Evaluate calibration approach
  - Assess measurement accuracy
- **Small, ground-based**
  - 24 receiving elements - 8 (9) per Y-arm
  - Operating at 50-55 GHz
  - 4 tropospheric AMSU-A channels: 50.3 - 52.8 - 53.71/53.84 - 54.4 GHz
  - Implemented with miniature MMIC receivers
  - Element spacing as for GEO application (3.5 λ)
  - FPGA-based correlator
  - All calibration subsystems implemented





Now undergoing testing at JPL!

Performance so far is excellent

Test Results: Solar Transit

GeoSTAR taken outside to observe the sun

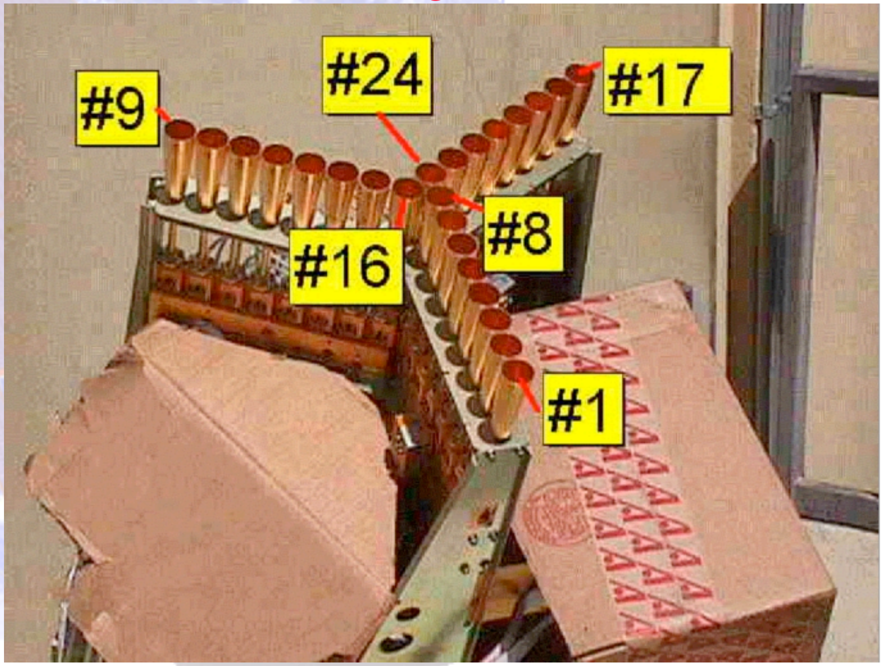
Pointed upwards at 45° elevation angle

About 80 minutes of data during transit through ~20° field of regard

Solar heating of instrument quickly became prominent —> Shielding with cardboard!

Initial configuration

Final configuration

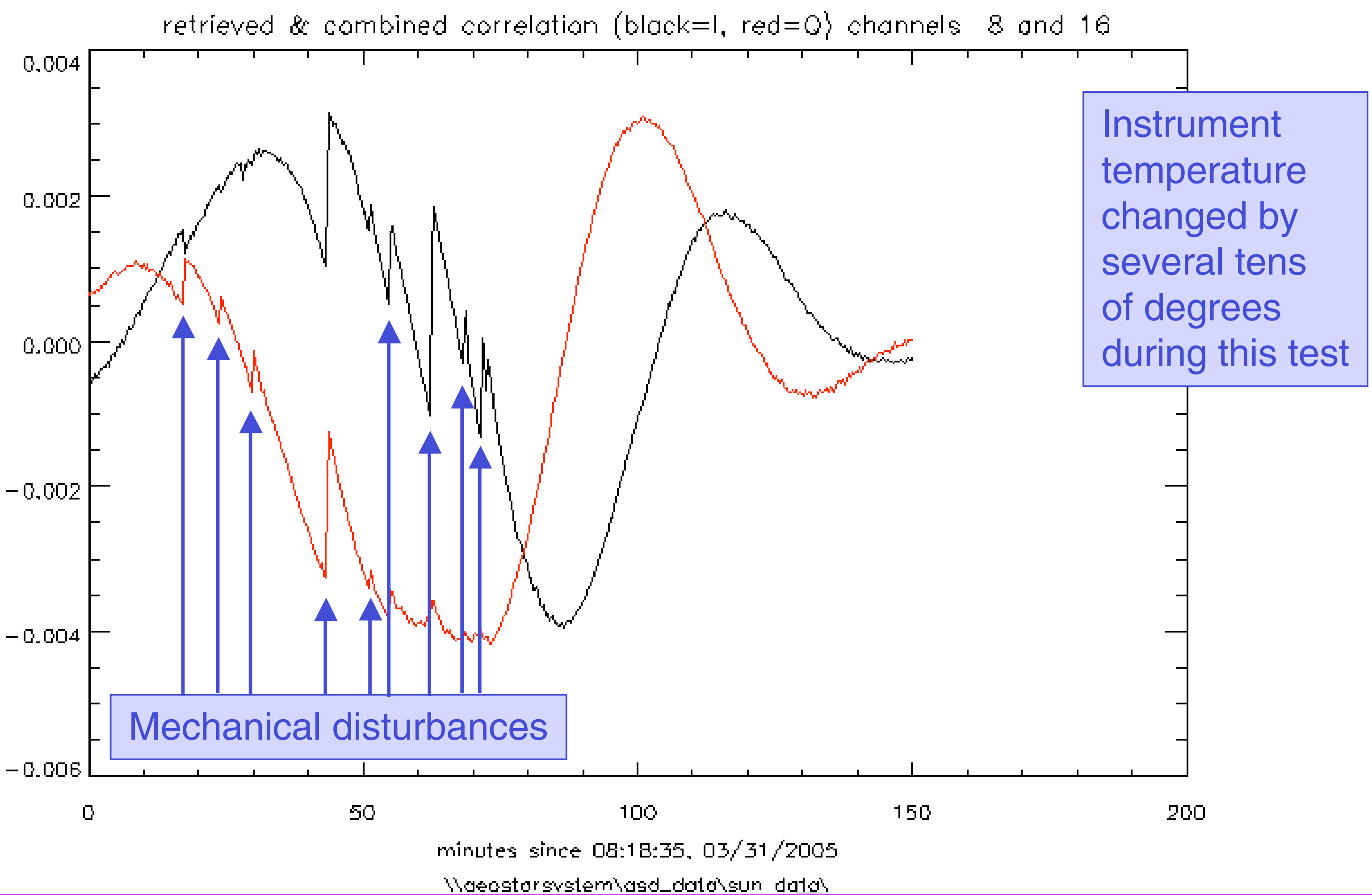


Note: During installation of shielding the instrument was bumped several times - can be seen in data

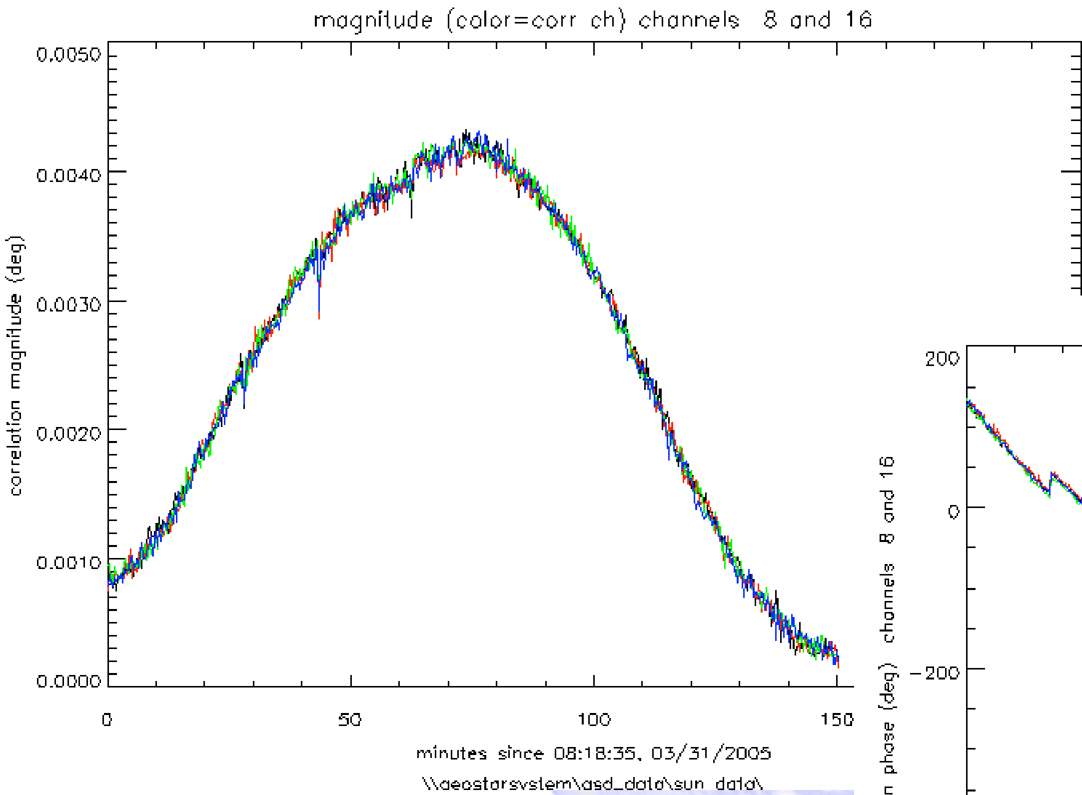
Solar Transit: Raw Correlations

Example: Receivers 8 & 16 (shortest baseline)

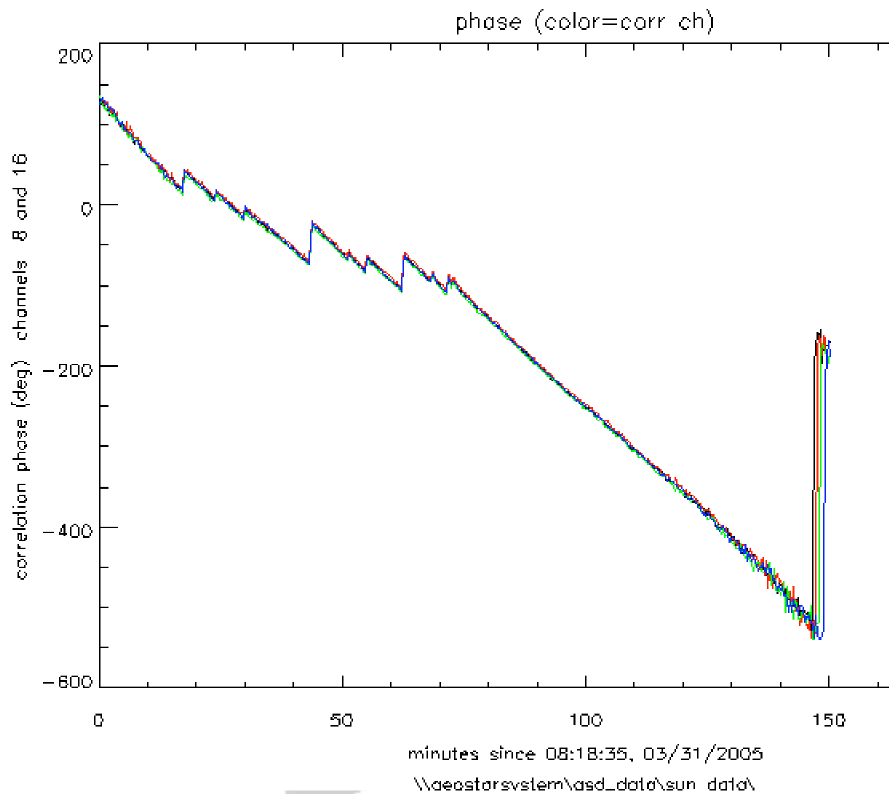
Discontinuities are caused by engineer bumping into instrument while arranging shielding against solar heating of instrument



Solar Transit: Computed Amplitude & Phase



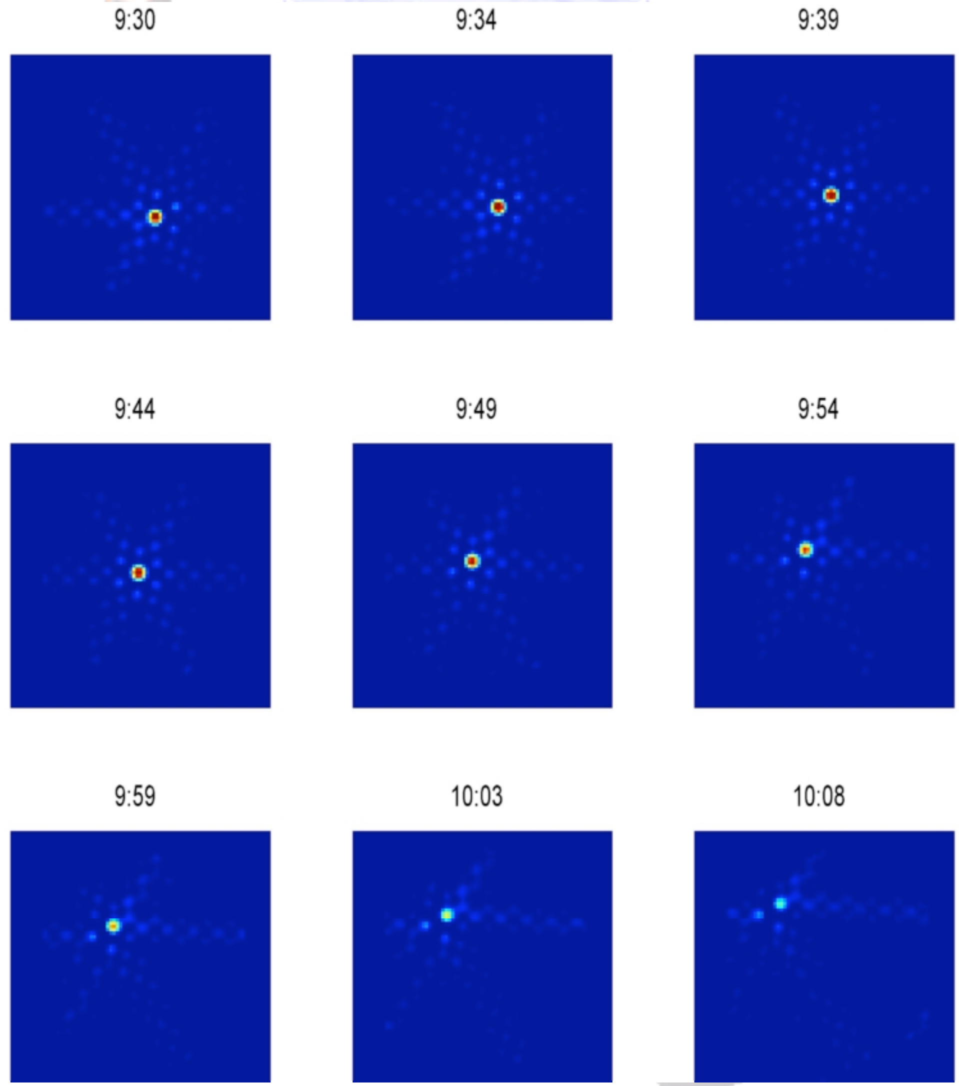
Same receiver pair (8 & 16)



Different colors represent LO phase, which is rapidly switched to null out phase biases

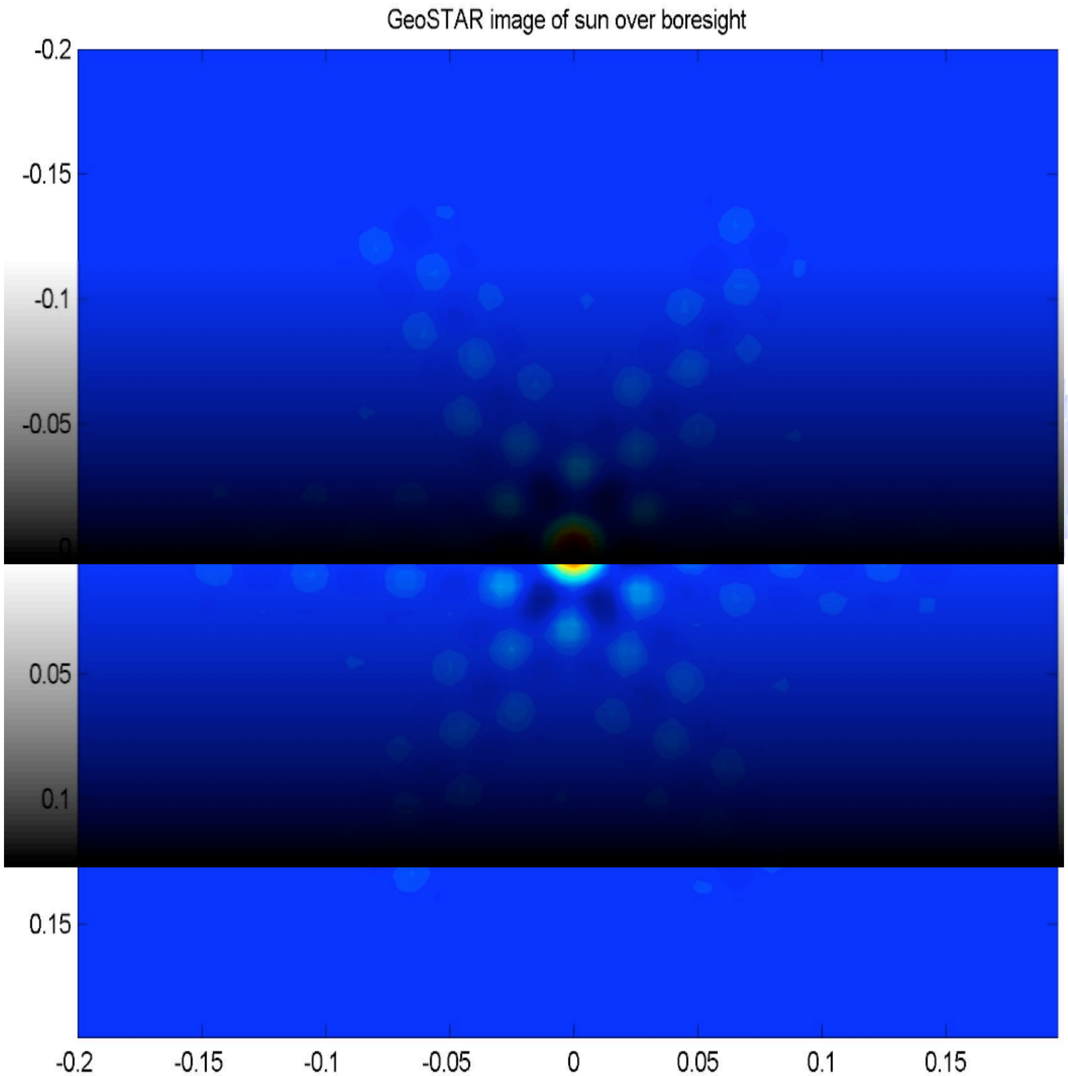
Solar Transit: Reconstructed Tb Images

Sun is about 4000 K in this 50-GHz channel

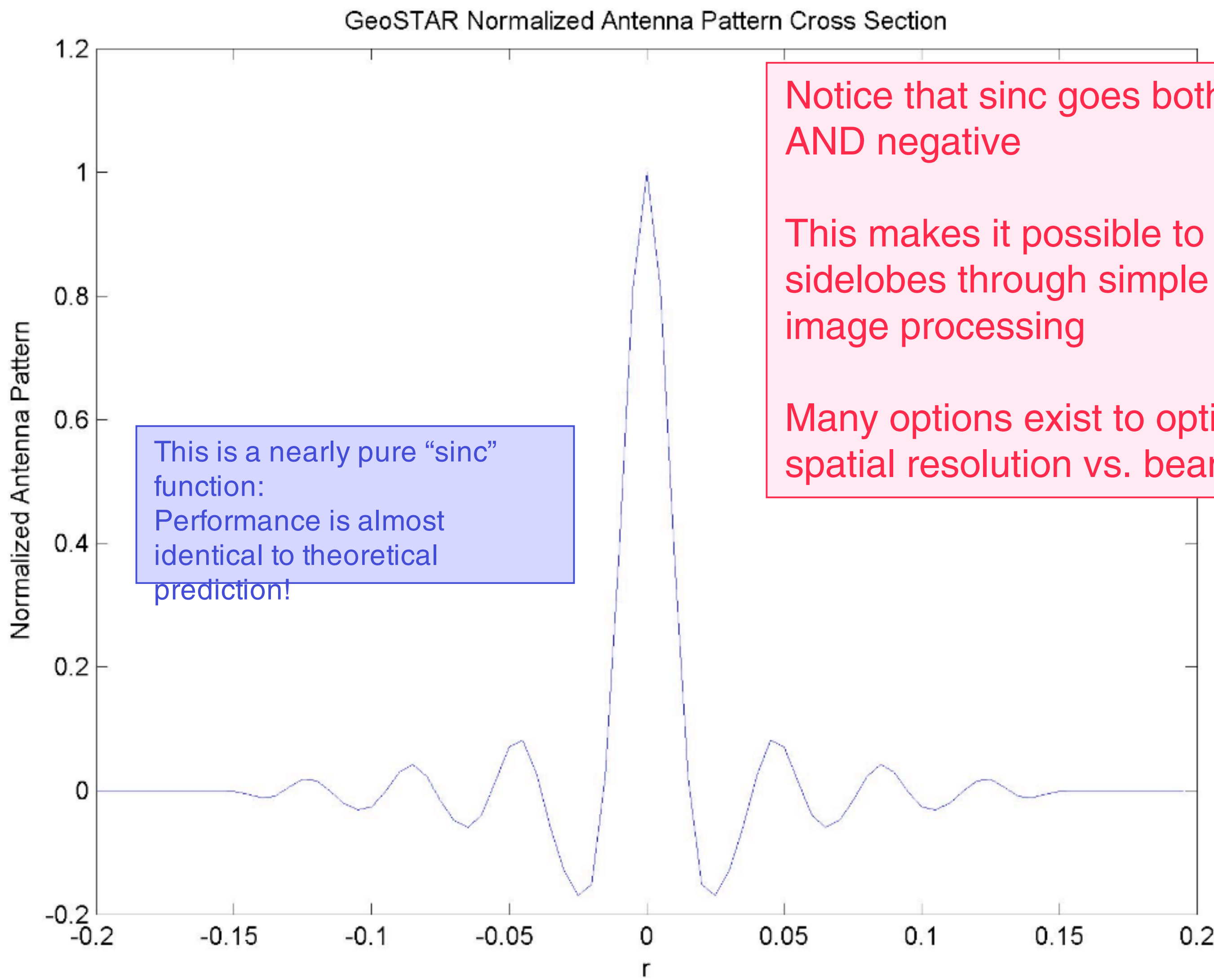


Times in PDT

Solar Transit: Raw Antenna Pattern



Solar Transit: Raw Antenna Pattern - 2



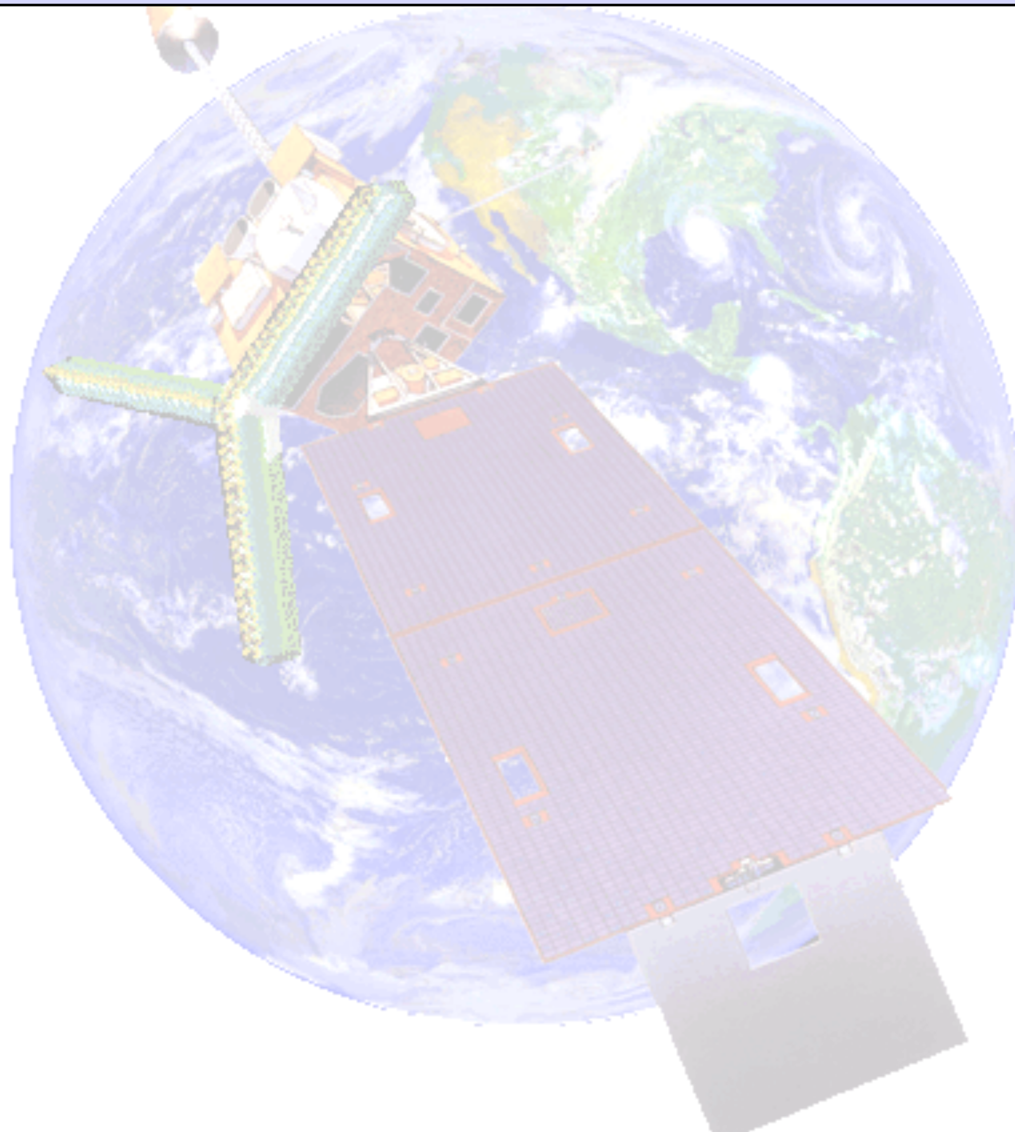
This is a nearly pure "sinc" function:
Performance is almost identical to theoretical prediction!

Notice that sinc goes both positive AND negative

This makes it possible to remove sidelobes through simple linear image processing

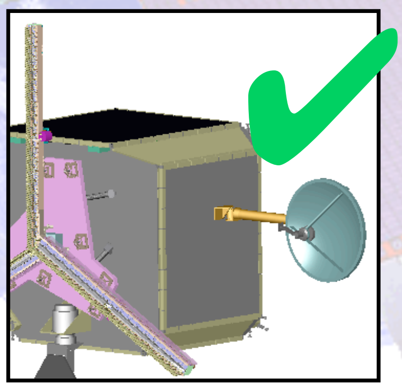
Many options exist to optimize spatial resolution vs. beam efficiency

Solar Transit: Animation Sequence

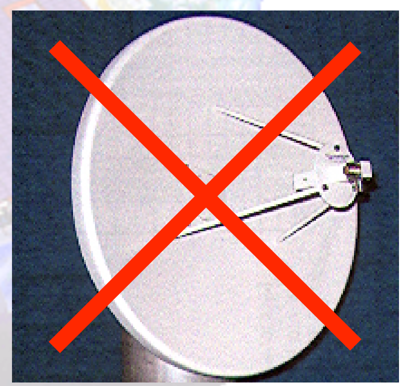


GeoSTAR vs. Real-Aperture Approach

Feature	GeoSTAR	Real aperture
Aperture size	Any size	Limited
Scanning	No scanning	Mechanical scanning
Spatial coverage	Full disk	Problematic
Spectral coverage	One array per band	One antenna/N receivers
Accommodation	Easy	Difficult
Power consumption	Moderate	Moderate
Platform disturbance	None	High
Technology risk	High – now being retired	Moderate to high

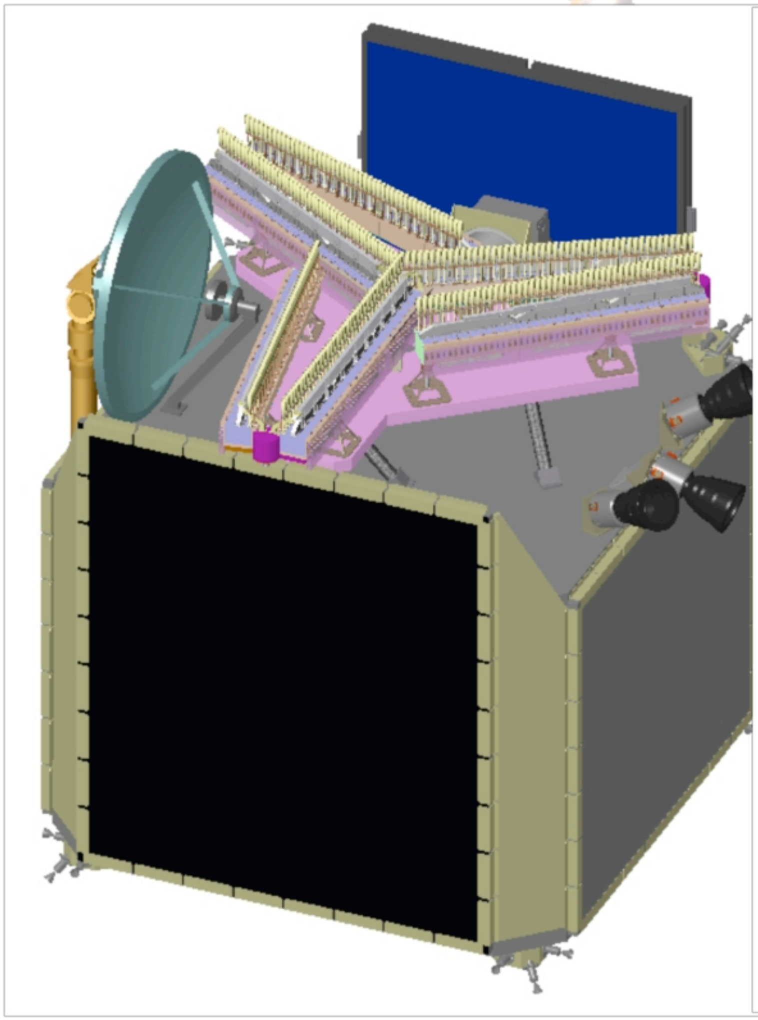


YES!

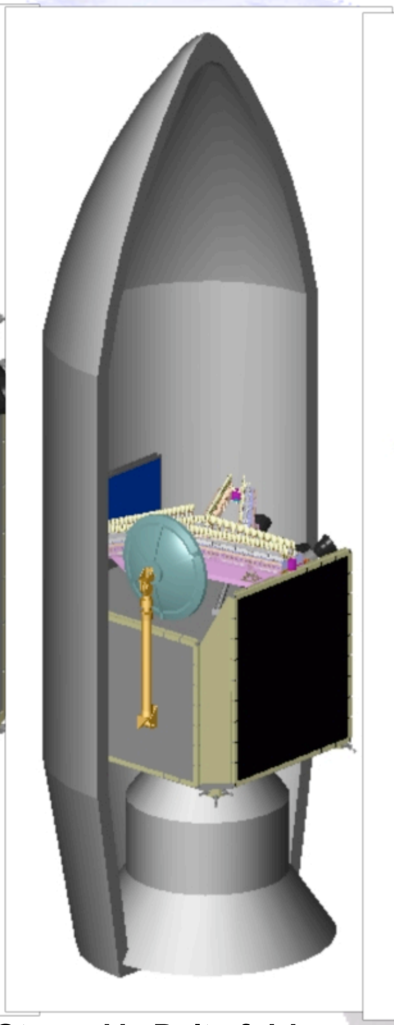


NO!

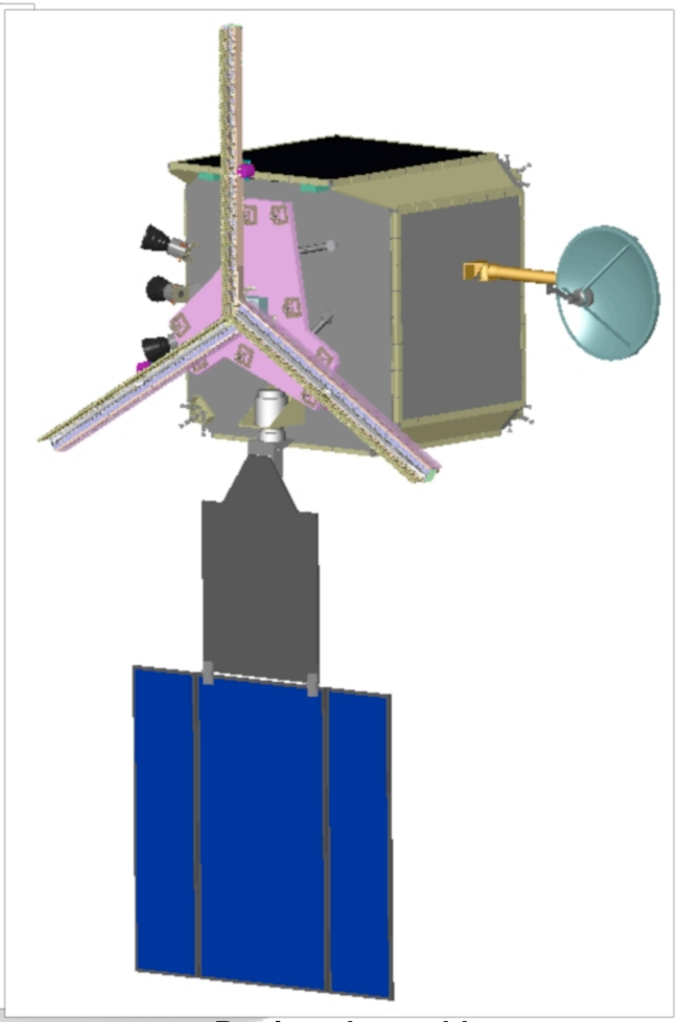
Accommodation Studies



Array arms folded for launch



Stowed in Delta fairing



Deployed on-orbit

Ball Aerospace

GEO Roadmap

- **Prototype: 2003-2005**
  - Fully functional system now being tested & characterized
- **Further risk reduction: 2005-2008**
  - Develop 183-GHz compact/lightweight multiple-receiver modules
  - Develop efficient radiometer assembly & testing approach
    - Reduce cost per receiver
  - Migrate correlator design & low-power technology to rad-hard ASICs
- **Space version (PFM): ~2008-2013**
  - Start formulation phase in 2008
  - Ready for launch in 2013 - Launch on GOES-S in 2014
- **Demonstration mission: ~2014-2015**
  - Joint NASA/NOAA mission
- **Transition to operational: ~2015**
  - Part of operational GOES

The GeoSTAR Team

Bjorn Lambrigtsen (JPL)	Science lead (PI)
William Wilson (JPL)	Task Manager (Co-I)
Alan Tanner (JPL)	System Engineer (Co-I)
Todd Gaier (JPL)	MMIC receivers (Co-I)
Pekka Kangaslahti (JPL)	MMIC receivers
Chris Ruf (U. Mich.)	Correlators & electronics (Co-I)
Jeff Piepmeier (GSFC)	Correlator subsystem & testing (Co-I)
Shyam Bajpai (NOAA)	Science advisory board
James Shiue (GSFC)	Science advisory board

Finally, Something Entirely Different!

HAMSR (built under IIP-1) to fly in Costa Rica TCSP hurricane field campaign during July 2005